JPRS-UEQ-91-006
18 JUNE 1991

Foreign Broadcast Information Service
50 ANNIVERSARY 1941 - 1991

JPRS Report

Science & Technology

USSR: Engineering & Equipment

19980116 221

JPRS-UEQ-91-006
18 JUNE 1991

SCIENCE & TECHNOLOGY

USSR: ENGINEERING & EQUIPMENT

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UDC 593.3

STUDY OF DYNAMICS OF CIRCULAR RING STRUCTURES ON PROGRESS-40 CARGO SPACECRAFT

917F0158A Kiev DOKLADY AKADEMII NAUK UKRAINSKOY SSR: SERIYA A -- FIZIKO-MATEMATICHESKIYE I TEKHNICHESKIYE NAUKI in Russian No 11, 1990 (manuscript received 14 Aug 90) pp 36-43

[Article by academician B. Ye. Paton, Yu. P. Semenov, P. M. Belousov et al., Kiev Construction Engineering Institute]

[Text] A space experiment to unroll two large structures 20 m in diameter each, which use drives from material having a memory effect for unrolling, was conducted on the Progress-40 spacecraft and the Mir orbital station during the period from 3 through 5 March 1989.

The process of unrolling and shaping these structures under space flight conditions was studied experimentally, and the stiffness and dynamic characteristics of the unrolled loop structures during dynamic operations with the cargo spacecraft were studied.

The free vibrations of large circular structures and their transient motions, caused by programmed progressive and rotational maneuvers of the cargo spacecraft, were calculated in preparation of the experiment.

Let us consider the problems of mathematical modeling of the dynamics of the carrier-ring system, the center of mass of which moves in a circular orbit about the earth. When performing maneuvers of the carrier according to the given program, the rings connected to it perform complex motion, consisting of translational motion of the body itself and the relative motion of the rings with respect to it. Let us disregard the orbital motion caused by gravity and inertia and let us assume that the system is free to study the dynamics of relative motion of the rings. Let us introduce the inertial coordinate system O_aXYZ and the system O_cxyz, rigidly bound to the carrier so that its axes coincide with the principal central axes of the system, and axis O_cz passes through the centers of rod rings, while axis O_cx is perpendicular to their plane.

The equations of dynamic equilibrium of the deformed element of the rod ring are represented in the form [4]

$$\frac{\tilde{d}\mathbf{F}}{ds} + \boldsymbol{\omega} \times \mathbf{F} + \mathbf{f} = 0, \quad \frac{\tilde{d}\mathbf{M}}{ds} + \boldsymbol{\omega} \times \mathbf{M} + \boldsymbol{\tau} \times \mathbf{F} = 0, \tag{1}$$

where **F** is the internal force vector, **M** is the internal moment vector, s is a coordinate measured along the axis of the line of the rod by the distance from some initial point to the current point, **f** is the vector of the external load intensity, which also includes the force of inertia, τ is the unit vector of the tangent to the axial line of the rod, ω is a Darby vector, and $\tilde{d}/ds$ denotes the local derivative.

Let us introduce the coordinate system (u, v, w), bound to the considered cross-section of the rod, axis w of which is directed along the tangent to the flexible line, and axes u and v are directed along the principal central axes of inertia of the cross-sectional area.

Projections M_u, M_v, and M_w of moment **M** onto the corresponding axes are expressed by the stiffnesses upon bending of A and B and by twisting of C, and also of curvature p, q of element ds and twisting r of the rod axis by the relations

$$M_u = A(p - p_0), \quad M_v = B(q - q_0), \quad M_w = C(r - r_0), \tag{2}$$

in which the values of p, q, and r for a deformed state of the rod are dentoed by zero.

Let us supplement system of equations (1) and (2) kinematically by Frenier equations [1]

$$\frac{d\boldsymbol{\tau}}{ds} = \frac{\mathbf{n}}{\rho}, \quad \frac{d\mathbf{n}}{ds} = -\frac{\boldsymbol{\tau}}{\rho} + \frac{\mathbf{b}}{T}, \quad \frac{d\mathbf{b}}{ds} = -\frac{\mathbf{n}}{T}. \tag{3}$$

Here **n** and **b** are unit vectors of the normal and binormal and ρ and T are the radii of curvature and twisting.

Let us also write the equations

$$\frac{dx}{ds} = \tau_x, \quad \frac{dy}{ds} = \tau_y, \quad \frac{dz}{ds} = \tau_z. \tag{4}$$

The system of solving equations (1)-(4), formulated in the domain of variation $0 \leq s \leq S$ of independent variable s has a common 18th order.

The first six integrals, which follow from the conditions of orthonormalization of the Frenier basis,

$$|\tau| = 1, \quad |n| = 1, \quad \tau \cdot n = 0, \quad \tau \times n = b$$

close the system of solving equations and permit us to avoid redetermination of it.

To construct the vibration equations of the rod, let us use the D'Alambert principle and let us represent the force acting on it in the form

$$f = -\gamma a, \tag{5}$$

where γ is the linear density of the rod and $\mathbf{a}$ is the acceleration vector of the element of the rod in system $O_a XYZ$.

Let us use the Coriolis formula [2] $a = a_e + a_r + a_c$, where $\mathbf{a}_r = \dddot{x}\,\mathbf{i} + \dddot{y}\,\mathbf{j} + \ddot{z}\mathbf{k}$ is relative acceleration, $a_e = a_0 + \varepsilon \times \rho + \Omega \times (\Omega \times \rho)$ is translational acceleration, $a_c = 2\Omega \times (\dot{x}\mathbf{i} + \dot{y}\mathbf{j} + \dot{z}\mathbf{k})$ is Coriolis acceleration, $\mathbf{a}_0$ is the acceleration of the center of mass of the carrier, $\mathbf{\Omega}$ and ϵ are vectors of the angular velocity and acceleration of the carrier, **i**, **j**, and **k** are unit vectors of system $O_c XYZ$, and $\rho = xi + yj + zk$; differentiation with respect to t is denoted by the dot.

Since vectors $\mathbf{a}_e$, $\mathbf{a}_r$, and $\mathbf{a}_c$, used for calculation of **f**, are calculated in coordinate system $O_c XYZ$, we initially find its projections

$$f_x = -\gamma \{\varepsilon_y z - \varepsilon_z y + [\Omega_x \Omega_y y - (\Omega_y^2 + \Omega_z^2) x + \Omega_x \Omega_z z] + \ddot{x} + 2(\Omega_y \dot{z} - \Omega_z \dot{y})\},$$

$$f_y = -\gamma \{\varepsilon_z x - \varepsilon_x z + [\Omega_y \Omega_x x - (\Omega_x^2 + \Omega_z^2) y + \Omega_y \Omega_z z] + \ddot{y} + 2(\Omega_z \dot{x} - \Omega_x \dot{z})\},$$

$$f_z = -\gamma \{\varepsilon_x y - \varepsilon_y x + [\Omega_y \Omega_z y - (\Omega_x^2 + \Omega_y^2) z + \Omega_x \Omega_z x] + \ddot{z} + 2(\Omega_x \dot{y} - \Omega_y \dot{x})\},$$

from which by formulas

$$f_u = (f_x n_x + f_y n_y + f_z n_z)\cos\chi + (f_x b_x - f_y b_y + f_z b_z)\sin\chi,$$
$$f_v = -(f_x n_x + f_y n_y + f_z n_z)\sin\chi + (f_x b_x - f_y b_y + f_z b_z)\cos\chi,$$
$$f_w = f_x \tau_x + f_y \tau_y + f_z \tau_z \quad (\chi = \operatorname{arctg}(p/q))$$

we turn to components f_u, f_v, and f_w, used in equations (1).

Having substituted ordinary derivatives for independent variables s and t in equations (1)-(4) by partial derivatives, we find the solving system of nonlinear equations of relative vibrations of the rings.

When studying the dynamics of the entire system, one must construct the equations of motion of the carrier and solve them jointly with the equations of motion of the rings. To do this, let us use the theorems on variation of the momentum **Q** and of the moment of momentum **K** of the carrier in the forms

$$\frac{d\mathbf{Q}}{dt} = \mathbf{R} + F^a, \quad \frac{d\mathbf{K}}{dt} = \mathbf{M}^R - \mathbf{M}^a, \tag{6}$$

where **R** and $\mathbf{M}^2$ are the principal vector and principal moment of reactions at the points of finishing of flexible rings, caused by their elastic deformation upon vibrations of the system, and $\mathbf{F}^a$ and $\mathbf{M}^a$ are the principal vector and principal moment of all active forces.

Using equations (1)-(6), the dynamics of the induced and free motions of the system is studied. Let us dwell on the results of solving the problems of free oscillations.

Let us limit ourselves to calculation of the lower values of the range of vibration frequencies and to construction of the corresponding forms. This permits one to turn from the initial continual problem to the corresponding discrete problem and to consider only a finite number of degrees of the system.

Let us assume that the vibrations of the system are determined by time-dependent displacements of the system of its discrete points

where N is the number of discrete points. The equations of free motions of the system can then be represented in matrix form

$$M\ddot{\mathbf{X}} + K\mathbf{X} = 0, \tag{7}$$

where **X** is the vector of displacements of the nodal points of the system, M is the matrix of masses, and K is the matrix of the stiffness of the discrete elements.

Matrix M is determined by the mass of each extended element, concentrated at the nodal points.

The stiffness matrix K can be determined by using the property $K = \Phi^{-1}$, where Φ is a pliancy matrix. The elements of matrix Φ are the displacements along the permissible couplings of the directions upon

action of the corresponding unit concentrated force on the node [6]. They are found as a result of solving the problems of the dynamic equilibrium of the rings upon corresponding steady translational and rotational motions of the system [4].

Assuming that free motion of the system has the form of harmonic vibrations, let us represent the solution of the system in the form $\mathbf{X}(t) = \mathbf{H} \sin \omega t$, where $\mathbf{H}$ is the vector of the form of vibrations and ω is the circular frequency corresponding to it. Substituting this solution into (7), we find

$$(K - \omega^2 M)\,\mathbf{H} = 0. \tag{8}$$

The eigenvalues ω_i and the eigenvectors $\mathbf{H}_i$ are calculated using the QR-algorithm.

(1) Номер формы	(2) Период, с (T_i)	(3) Частота, рад/с (ω_i)	(4) Угол поворота, рад	(5) Перемещение по направлению оси
1	2	3	4	5
1	175,75	0,0357	—	Ox
2	132,54	0,0474	$\varphi_y=0{,}0189$	Ox
3	62,46	0,1006	—	Ox
4	57,02	0,1102	$\varphi_z=0{,}0159$	Ox
5	40,13	0,1566	—	Oy
6	26,86	0,2340	—	Ox
7	26,76	0,2348	$\varphi_y=0{,}00389$	Ox
8	15,65	0,4016	$\varphi_x=-0{,}0387$	Oy
9	14,29	0,4398	—	Ox
10	14,26	0,4408	—	Oz
11	14,24	0,4411	$\varphi_y=0{,}000008$	Oz
12	14,15	0,4439	$\varphi_x=0{,}0319$ $\varphi_z=0{,}0032$	Oy
13	8,96	0,7014	—	Ox
14	8,95	0,7017	$\varphi_y=0{,}00105$	Ox
15	6,82	0,9207	—	Oz
16	6,37	0,9861	$\varphi_x=0{,}0418$	Oz
17	6,333	0,9921	—	Ox
18	6,328	0,9930	$\varphi_x=0{,}0419$ $\varphi_z=0{,}0003$	Oz

KEY:

1. Number of form
2. Period, s(T_i)
3. Frequency, rad/s (ω_i)
4. Angle of rotation, rad
5. Displacement in direction of axis

A total of 18 values of the spectrum of the natural vibration frequencies of the carrier-elastic ring system is calculated by the developed method, and the corresponding forms of motion are constructed. The results of calculation are presented in the table. The ordinal

numbers of the eigenvalues are given in the first column, the length of the vibration period T_i is given in the second column, the corresponding values of the circular frequencies ω_i are given in the third column, the amplitude values of the angles of rotation of the carrier with respect to the corresponding axis are given in the fourth column, and the axis, in the direction of which the greatest displacement of the typical point of the ring is realized, is indicated in the fifth column. The forms of vibrations of the rings are normalized so that the amplitude value of the maximum displacement is equal to one.

The axonometric images of the first six forms of natural vibrations are shown in Figure 1 with respect to a fixed coordinate system. Two coordinate systems--a fixed system OXYZ and coordinate system Oxyz, rigidly bound to the carrier, rotated during its vibrations with respect to the fixed system--are also presented in it. The movable coordinate system does not happen in cases when the rotational motion of the body is absent. The forms of vibrations of the rings are normalized in all figures so that the value of the maximum relative displacement is equal to 1/5 of the diameter of the ring.

As calculations showed, the vibration modes that permit rotation of the carrier have higher frequencies, compared to the descending modes of natural vibrations of the rings, rigidly fastened to a fixed support.

Upon study of the dynamic and strength characteristics and also of the controllability of the cargo spacecraft with unfolded large annular structures, the following problems were solved:

1) experimental determination of the frequency and decrement of the main tone of vibrations of the structures;

2) a check of the capability of the structures of restoring a given form after the cargo spacecraft completed turns and correction pulses;

3) a check of the results of preliminary calculations of the structural dynamics and applicability of the calculating models to be used.

The most complete information, including a television image of the vibrations of one of the annular structures, transmitted from the cargo spacecraft (Figure 2), during the experiment was found in two sessions, in which the cargo spacecraft accordingly performed a correcting pulse $\Delta V = 0.6$ m/s and a programmed yawing turn by angle $\varphi = 120^\circ$ at angular velocity $\omega = 0.67^\circ$/s.

Symmetrical vibrations of the structures were excited with period 190 s during the correcting pulse. The points of the rings most remote from the carrier were deflected from the neutral position by 11 m. These values of the period and amplitude of vibrations essentially coincided with the results of earlier calculations. It should be noted that the actual period of vibrations was determined immediately from three

sources: by a television image from the cargo spacecraft, by a report of the crew of the "Mir" spacecraft and by telemetry data.

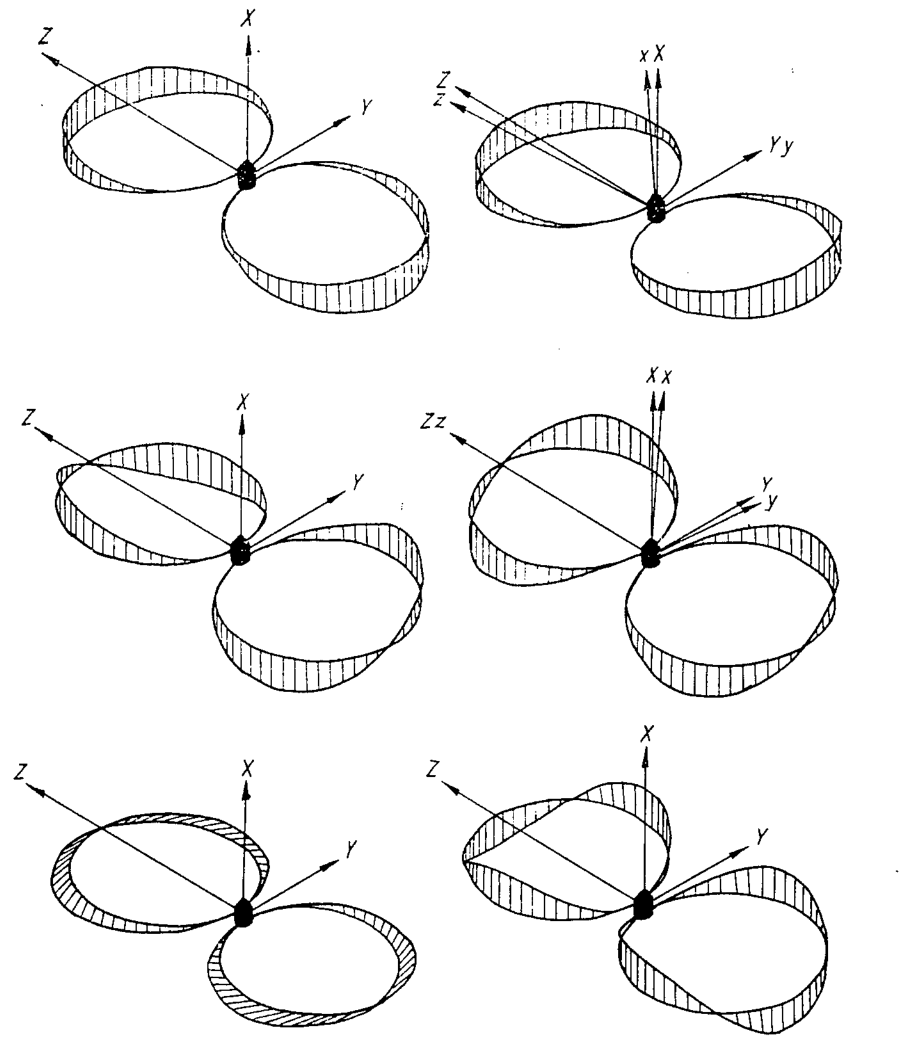

Figure 1

The dissipative properties of the large annular structures were studied upon analysis of the vibrations caused by the correcting pulse, which are difficult to determine by calculation or by ground tests. Observing these vibrations directly, the crew of the "Mir" orbital station noted slow damping of them, while preliminary analysis of the telemetry data permitted an estimation of the logarithmic decrement of $\delta = 0.05$.

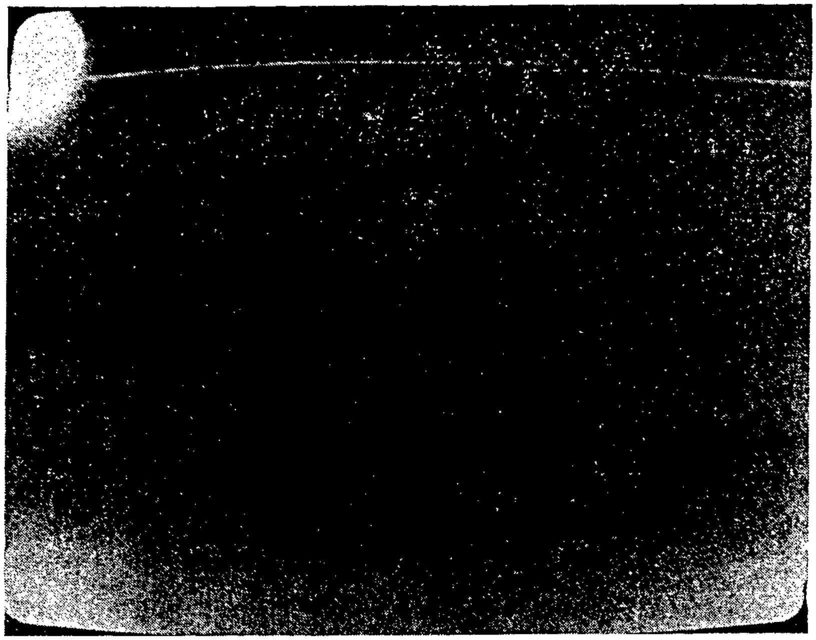

Figure 2

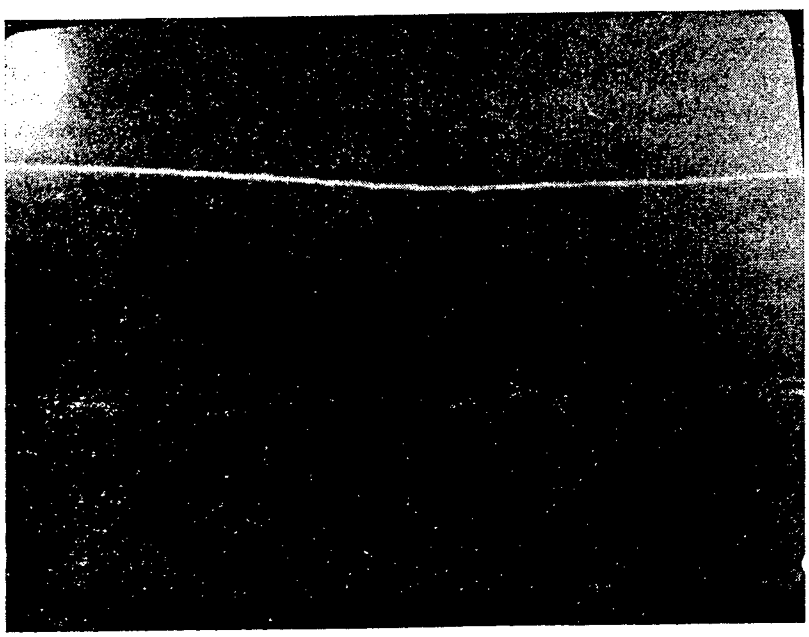

Figure 3

When considering the methods of improving the controllability of a spacecraft with large unfolded annular structures and taking into

account the weak damping of vibration of these structures, main attention should be devoted to dynamic suppression of vibrations, excited during maneuvers of the spacecraft, rather than to passive damping. Thus, the dynamic effect of essentially total instantaneous correction of vibrations of the structure as a result of selecting the moment of stopping the rotation of the spacecraft can be specifically used as one of the principles of selecting its optimal control.

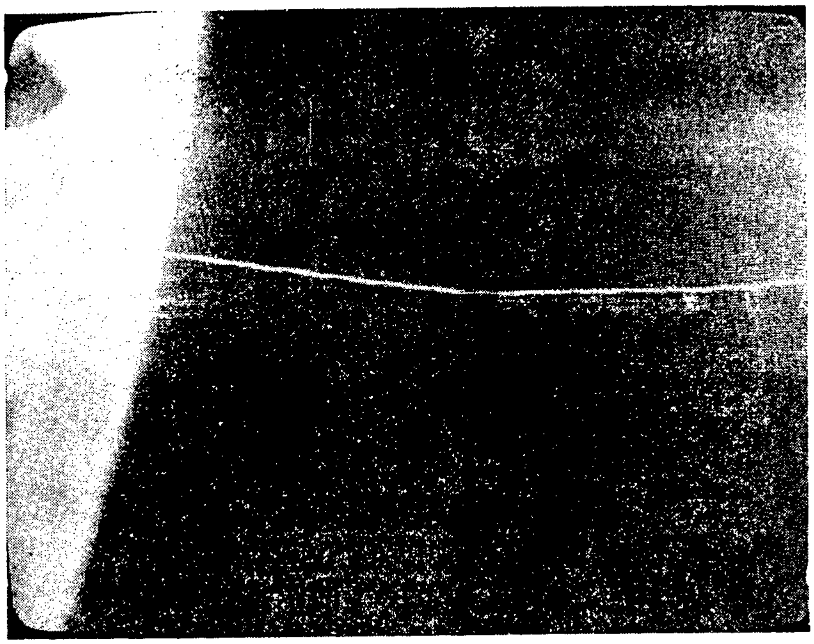

Figure 4

The dynamic effect of essentially total kinematic suppression of vibrations was demonstrated when the Progress-40 spacecraft performed a programmed turn, and the angle of rotation of $\varphi = 120^\circ$ was previously calculated on the basis of the measured value of the actual period of the main tone of vibrations of the annular structures--T = 190 s and of the nominal rotational velocity of the cargo spacecraft $\omega = 0.67^\circ/s$, with the calculation that the structure performed a single vibration during the turn of the cargo spacecraft.

It was obvious from the television image from the Progress-40 spacecraft (Figures 2-4) that the annular structure performed one vibration during the turn, and that it essentially stopped in the neutral position at the moment of completion of the turn and the beginning of stabilization of the cargo spacecraft. The theoretical conclusion of the possibility of rapid suppression of vibrations, having the value of the optimal control of the dynamics of large structures when working out the methods, was thus confirmed.

Comparison of the results of calculation and data of full-scale tests indicates that they are in satisfactory agreement.

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UDC 539.3:534.1:531.383

ON ERRORS OF SOLID-STATE WAVE GYROSCOPES DURING PROGRESSIVE VIBRATION OF BASE

917F0159A Kiev DOKLADY AKADEMII NAUK UKRAINSKOY SSR: SERIYA A -- FIZIKO-MATEMATICHESKIYE I TEKHNICHESKIYE NAUKI in Russian No 11, 1990 (manuscript received 4 Jun 90) pp 25-28

[Article by N. V. Vasilenko, S. A. Sarapulov, and A. M. Pavlovskiy, Kiev Polytechnical Institute]

[Text] The effect of progressive and angular vibration on the motion of traditional mechanical gyroscopes has now been studied. However, the problem of the effect of vibration of the base on the accuracy of the new inertial information meter--the solid-state wave gyroscope (TVG), which is of considerable interest, has been insufficiently studied [1-4].

The nonlinear dynamics of a solid-state wave gyroscope with imperfect cavity on a progressively vibrating base is considered in this paper.

The state of the object is given by generalized coordinates $p_n(t)$ and $q_n(t)$, corresponding to conjugate natural forms of vibrations of a hemispherical cavity $U_{kn}(\theta)\cos n\varphi$, $U_{kn}(\theta)\sin n\varphi$ $(k=1, 2, 3)$, which are introduced by the approximation

$$u_1 = \sum_n U_{1n}(p_n \cos n\varphi + q_n \sin n\varphi),$$

$$u_2 = \sum_n U_{2n}(p_n \sin n\varphi - q_n \cos n\varphi),$$

$$u_3 = \sum_n U_{3n}(p_n \cos n\varphi + q_n \sin n\varphi),$$

where angle φ is counted in the circumferential direction and angle θ is formed by the axis of symmetry and by the internal normal. Application of the Bubnov-Galerkin procedure to the nonlinear equations of motion of the cavity on a vibrating base [4] with regard to representation of

defects of a hemispherical dome in the form of expansions into a Fourier series by circumferential angle φ [5] results in ordinary differential equations in generalized coordinates that describe nonlinear vibrations of an imperfect cavity on a progressively vibrating base. Let us consider resonant vibrations when the external perturbation frequency χ is a multiple of the working frequency ω_2 (the case of excitation of a second pair of natural forms of vibrations in the cavity, n = 2, is of interest for applied problems [1, 6]), assuming that there is no internal resonance in the system. Equations that describe the dynamics of the main form have the form

$$\begin{gathered}
(m_0+\varepsilon m_{11})\ddot{q}_2+\varepsilon m_{12}\ddot{p}_2+2\varepsilon K_0\Omega\dot{p}_2+\varepsilon\lambda_0\dot{q}_2+(c_0+\varepsilon c_{11})q_2+c_{12}p_2+\\
+\varepsilon(H_0p_0q_2+H_1q_1p_1)+\varepsilon f_1+0(\varepsilon^2)=0, \qquad (1)\\
(m_0+\varepsilon m_{22})\ddot{p}_2+\varepsilon m_{21}\ddot{q}_2-2\varepsilon K_0\Omega\dot{q}_2+\varepsilon\lambda_0\dot{p}_2+(c_0+\varepsilon c_{22})p_2+c_{21}q_2+\\
+\varepsilon(H_0p_0p_2+H_2q_1^2+H_3p_1^2)+\varepsilon f_2+0(\varepsilon^2)=0,
\end{gathered}$$

where

$$f_1=m_1W_{OX}+m_2W_{OY}+m_3W_{OZ},\ f_2=m_1^*W_{OX}+m_2^*W_{OY}+m_3^*W_{OZ}.$$

Here m_0, c_0, K_0 and λ_0 are the coefficients of inertia and stiffness, and gyroscopic and damping coefficients of an ideal cavity, respectively, Ω is the angular rotational velocity of the cavity about its own axis of symmetry (it is considered a slowly variable time function, i.e., we disregard terms with $\dot{\Omega}$ and Ω^2), m_{ij} and c_{ij} (i, j = 1, 2) are perturbations of the coefficients of inertia and stiffness due to errors in manufacture of the hemispherical cavity (the fourth harmonics of expansion of the defects into a Fourier series [5]), and $m_{12}=m_{21}$, $c_{12}=c_{21}$, $m_{11}=-m_{22}$, $c_{11}=-c_{22}$; m_l, m_l^* $(l=1,\ 2,\ 3)$ are perturbations of the inertial characteristics of the cavity, m_3 and m_3^* correspond to the second component of the defect in Fourier expansions, m_1, m_1^*, m_2, and m_2^* are the first and third harmonic, $W_{0X}=-\chi^2X_0\cos\chi t$, $W_{0Y}=-\chi^2Y_0\cos\chi t$, $W_{0Z}=-\chi^2Z_0\cos\chi t$ are projections of the vector of linear accelerations of the base onto axes X, Y, and Z of a coordinate system rigidly bound to pole O of the cavity, and axis OZ coincides with the axis of symmetry of the cavity, q_1, p_1, and p_0 are generalized coordinates that characterize the motion of a hemispherical cavity as a solid

$$\begin{gathered}
q_1=g_1X_0\cos\chi t,\ p_1=g_1^*Y_0\cos\chi t,\ p_0=g_0Z_0\cos\chi t,\quad g_0=\text{const},\\
g_1=\text{const},\quad g_1^*=\text{const},
\end{gathered}$$

where X_0, Y_0, Z_0 and χ are the amplitudes and frequency of external perturbation, H_0, H_1, H_2, and H_3 are constant coefficients with nonlinear terms, and ϵ is a small parameter.

Let us consider two important cases of vibration of the base.

Longitudinal vibration. The base moves along the axis of symmetry of the cavity ($Z = Z_0 \cos \chi t$). Analysis of equations (1) shows that the following resonance situations are possible in the system: a) $\chi = \omega_2 + \epsilon\sigma$, where σ is a detuning parameter. In this case, longitudinal vibration of the base results in excitation of "spurious" induced vibrations in the cavity. In zero approximation of the perturbation method [7], solution of the system of equations (1) has the form

$$q_2^{(0)} = Q(T_1)\exp(i\omega_2 T_0) + \bar{Q}(T_1)\exp(-i\omega_2 T_0),$$
$$p_2^{(0)} = P(T_1)\exp(i\omega_2 T_0) + \bar{P}(T_1)\exp(-i\omega_2 T_0),$$

where $T_n = \varepsilon^n t$; $\bar{Q}$, Q and P, P are complex conjugate amplitudes. Let us represent the complex amplitudes in exponential form

$$Q = a(T_1)\exp\{i[\alpha(T_1) + \sigma T_1]\},$$
$$P = b(T_1)\exp\{i[\beta(T_1) + \sigma T_1]\}.$$

Substitution of variables by formulas $b + ia = C\exp(2i\Psi)$, $\beta - \alpha = \phi$, $\alpha + \beta = \gamma$ permits us to write the condition of the absence of secular terms in the solutions of the first approximation $q^{(1)}{}_2$ and $p^{(1)}{}_2$ in new variables C, Ψ, φ, and γ. A real instrument has a control system that maintains vibrations of the cavity in the form of a standing wave, since, as shown in [8], it assumes fulfillment of the following conditions: $\phi = 0, \frac{\partial\gamma}{\partial T_1} = 0, \frac{\partial C}{\partial T_1} = 0.$ Taking the foregoing into account, we find a formula that determines the precession rate of the standing wave during functioning of a solid-state gyroscope due to the effect of longitudinal vibration

$$\Psi' = -\frac{K_0\Omega}{2m_0} + \frac{\chi^2 Z_0 \sin(\gamma/2)}{4m_0\omega_2 C}(m_3\cos 2\Psi - m_3^*\sin 2\Psi). \qquad (2)$$

Here $(\dot{\ldots}) = \frac{\partial(..)}{\partial T_1}$; $C = (b^2 + a^2)^{1/2}$, Ψ are the vibration amplitude and angle of orientation of the wave pattern, respectively, and $\omega_2 = (c_0/m_0)^{1/2}$ is the natural frequency of an ideal cavity. It follows from formula (2) that the integrating effect of a solid-state wave gyroscope will occur only at angular velocities Ω, which exceed the threshold value $\Omega_{\min} = \Delta m Z_0 \omega_2 / 2K_0 C$. Here $\Delta m = (m_3^2 + m_3^{*2})^{1/2}$, $\chi = \omega_2$.

b) $\chi = 2\omega_2 + 2\epsilon\sigma$. Longitudinal vibration excites "spurious" parametric vibrations. The equation that determines angle Ψ has the form

$$\Psi' = -K_0\Omega/2m_0. \tag{3}$$

It follows from equation (3) that longitudinal vibration in the given case does not result in an additional "spurious" component in the wave pattern.

Transverse vibration. The base moves in a plane perpendicular to the axis of symmetry of the cavity $(X = X_0 \cos\chi t,\ Y = Y_0 \cos\chi t)$. The following resonant situations are possible in the system:

$$\text{a)}\quad \chi = \omega_2 + \varepsilon\sigma,$$
$$\text{b)}\quad \chi = \frac{1}{2}\omega_2 + \frac{1}{2}\varepsilon\sigma.$$

In both cases, transverse vibration of the base results in excitation of "spurious" induced vibrations of the cavity. Expressions that determine the position of the wave pattern as a function of the angular rotational velocity and vibration parameters of the base have the form

$$\text{a)}\quad \Psi' = -(2m_0)^{-1}K_0\Omega + (4m_0\omega_2 C)^{-1}[(m_1X_0 + m_2Y_0)\cos 2\Psi - (m_1^*X_0 + m_2^*Y_0)\sin 2\Psi]\sin(\gamma/2),$$
$$\text{b)}\quad \Psi' = -(2m_0)^{-1}K_0\Omega + (4m_0\omega_2 C)^{-1}[H_1 g_1 g_1^* X_0 Y_0 \cos 2\Psi - (H_2 g_1^2 X_0^2 + H_3 g_1^{*2} Y_0)\sin 2\Psi]\sin(\gamma/2).$$

In the given case, we will also have some threshold value of the angular rotational velocity of the base, below which there is no integrating effect.

It follows from the studies that there are several mechanisms of errors in the operation of the instrument upon vibration of the base:

excitation of additional "spurious" vibrations of the cavity that lead to distortion of the readings of the instrument due to the presence of errors in manufacture of the cavity;

excitation of additional "spurious" vibrations due to the presence of nonlinear coupling (between generalized coordinates) that characterize intermodal interaction.

The results of the studies can be used in determining the dimensions of the zones of absence of the integrating effect of a solid-state wave gyroscope, the nominal value of the vibration amplitude of the cavity, and also when working out the requirements on the precision of manufacture of the cavity and on the vibration protection system.

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UDC 620.9.003.13:502.3

PROBLEMS OF ESTIMATING ECOLOGICAL IMPACT OF ENERGY-CONSERVING MEASURES

917F0055A Riga IZVESTIYA LATVIYSKOY AKADEMII NAUK in Russian No 4, 1990 (manuscript received 10 Apr 90) pp 98-102

[Article by V. A. Zebergs, L. L. Eihmanis, and I. Ya. Niedrite]

[Text] The problems of increasing the efficiency of utilizing fuel and energy resources are acquiring ever more timely value in all sectors of the national economy. Problems of energy conservation will determine to a great extent in the future the development of industry, transport, agriculture and the communal-everyday sector. The problem has special significance for Latvia under conditions of transition to independent forms of management and republic cost-accounting, since 85 percent of the fuel and 50 percent of the electric power are delivered from other regions. Along with this, the problem of adequate and real nature-conserving activity is valid. Interaction of facilities of the fuel and energy complex with the environment is an exceptionally important problem. On the one hand, the value of an uninterrupted effective energy supply of all sectors of the national economy is very high, and on the other hand, the fuel and energy complex has the most significant effect on the human habitat. Only centralized power enterprises discharge more than 40,000 tons of noxious materials annually in the atmosphere in Latvia, which comprises 21 percent of the total discharge in the republic.

The increasing pollution of the atmosphere is assuming a global nature today. Discharges of noxious and harmful pollutants into the atmosphere by many sectors of industry have a deleterious effect on living organisms, destroy the ozone layer, and contribute to the occurrence of acid rain. The reality of the greenhouse effect occurring is a consequence of variation of the structure of radiant heat transfer as a result of intensive utilization of thermal power systems. These phenomena may affect the entire country and even whole continents. Although scientists have different opinions on the time intervals and intensity of the ecological changes, nevertheless they are still significant, which requires urgent study.

A session of the General Assembly of the Academy of Sciences, devoted to discussion of the project of the main propositions of the Program of

Biospheric and Ecological Research of the USSR Academy of Sciences for the period up to 2015 in December 1988 noted that we are in the phase of anthropogenic effects on nature, when the processes of ecological degradation are even more local in nature, but global trends, hazardous for the biosphere as a whole, are already being detected on this background. This is the moment when the process of irreversible ecological changes can be stopped now through the efforts of people.

Outside of health and well-being, all our social goals and political and ecological ideals are impractical. Alternative versions of solving socioecological and technical problems must be worked out. Academician P. L. Kapitsa convincingly demonstrated the interdependence of the growth of the gross national product and energy production for all countries of the world. This means that if there is an increase of energy, there will also be an increase of the national product.

The time has come to combine the means of survival into a single complex, optimal in the given ecological situation [1]. This is a most important scientific task both on a global scale and for each country.

The Physics and Power Institute of the Latvian Academy of Sciences is participating in development of the section "Power engineering" of the general academic program of biospheric and ecological research for the period up to 2015. The topic being studied is a method of estimating the loss due to the effects of energy facilities. Problems of estimating the ecological impact of energy-conserving measures, which include analysis of the engineering solutions of energy conservation in industry and ecological zoning and dipersion of energy resources, structural shifts in industry, and their energy and ecological consequences, are being considered in the first phase of these studies. The studies are directed toward discovering the characteristic features of energy conservation with different layouts of energy conservation of enterprises, a rational structure of industry and with specific principles of estimating the ecological impact of energy-conserving plants, now used in Latvia.

Determination of the principles of ecological estimation of the engineering solutions of energy conservation in our republic is based on analysis of the characteristic features of natural conditions, functioning of the natural and technical environment, and of the state of the ecoosystems of the given territory. Thus, optimization calculations are made with regard to ecological factors under specific conditions of a corresponding region, but the principal approach to the problem is identical for all economic regions.

Analysis of the functioning of the territorial economic-ecological system of the Latvian Republic shows that its intensity determines the consequences of the ecological concept, implemented during the previous 5 years, which was constructed on the basis of hypertrophic development of industry, oriented toward extensive growth factors, and was not accompanied by a search for effective ways of reducing the energy and

resource capacity, and solution of environment protection problems. The main industrial centers at present--cities and urban agglomerations--have become areas of extensive negative transformation of the environment, the effect of which is very significant not only on the nature of adjacent territories, but also on the vast regions of river basins, and coastal waters of the sea. One must sometimes talk about the symptoms of a crisis state, when the parameters of the environment are approaching the permissible limits of changes, and suppression of reproductive capacities and exhaustion of the ecological capacity of the territory have been noted; therefore, intensification of the environmental protection trend now conducted outside economic reform is necessary, the ecology aspect of cost accounting is required, and this must be transformed to a reliable barrier on the path toward wasteful utilization of nature.

The current phase of development of the economy is characterized by a stable increase of the expenditures of social labor, embedded in environmental protection and in reproduction of natural resources. A growth of the scales of ecological investment increases the responsibility of each planning solution in this field, and imposes higher requirements on their effectiveness. At the same time, society needs optimal development of TEK [not further identified] as a necessary condition of enhancing the life level and national income. An objective need arises in this regard to establish interrelationships between the results of economic activity and its ecological consequences. Substantiation of the economy of production is an inseparable part of the management system that affects the selection of priorities in support of the national economy with natural and energy resources. The main causes of a negative effect of the national economy on the environment are imperfection of technology, an increase of the scales of production, and its concentration on a limited territory. The increase of energy consumption can be covered by 30-40 percent in the Latvian republic by introduction of energy-conservation technologies and scientifically substantiated standards of energy consumption [2].

Life persistently requires extensive analysis of the energy consumption of manufactured products. High losses of energy resources are formed due to the fact that we do much that is unnecessary, and even in weighted form. The unsubstantiated high materials consumption is accompanied by impermissibly high energy consumption. Recovery of secondary resources that yields significant energy conservation has not become widespread. The high degree of depletion of production funds in industry, which comprises more than 47 percent, also results in rational consumption of energy in our republic. This part of the morally and physically obsolete production funds is also a significant source of environmental pollution.

The fact that tenfold more funds are expended in the country on routine maintenance of operated equipment than is required for replacement of it indicates the redundancy of this practice [3].

Utilization of secondary energy resources can reach more than 46 percent in the future structure of measures on conservation of energy resources, while the use of energy-conserving technology in industry and in agriculture may reach approximately 38 percent [2].

An experimental lot of facade heat regulators is functioning successfully in Riga. The instruments, developed at FEI, contribute to conservation of energy resources and prevent overconsumption of thermal energy. The heat loss factor of new multistory buildings is 0.42-0.47 kilocalories per square meter, which is 25-30 percent higher than the optimal value.

Taking into account the ecological impact is of considerable significance in economic estimation of energy-conserving measures and in determination of the priority of implementing them with limited monetary and material funds. Analysis of the ecological impact is related to estimation of the consequences of discharges of energy sources that supply energy-conserving plants compared to traditional plants, which utilize a closed form of fuel (in the presence of scrubbing structures that provide the PDV [maximum permissible discharge] at the required PDK [maximum permissible concentration]). The consumption of energy resources on the energy supply of the drive of energy-conserving plants for use of secondary thermal resources is insignificant, and sometimes (utilization of TNU heat pumps) may reach 30 percent or more of the extracted alternative energy resources. Therefore, the ecological impact is determined by the difference in the amount of fuel burned for comparable variants (the drive of plants that conserve energy or generate the same amount of energy by the traditional method) and by the loss due to discharges. Estimation of the loss is determination of the expenditures, related to usefully generated (conserved) energy at comparable energy plants (per ton of conventional fuel). The economic impact of energy-conserving measures can generally be formulated with regard to the ecological loss due to discharges as

$$\Delta \text{з}'_{\text{эс}} = \Delta \text{з}_{\text{к}} + \Delta \text{з}_{\text{с}} + \Delta \text{з}_{\text{т}} + \Delta y, \qquad (1)$$

where $\Delta \text{з}'_{\text{эс}}$ is the specific economic impact of energy-conserving measures with regard to the ecological impact (rubles/t of conventional fuel), $\Delta \text{з}_{\text{к}}$ is the difference of the specific expenditures, dependent on capital investments on a traditional power plant operating on the close fuel cycle and on an energy-conserving plant, $\Delta \text{з}_{\text{с}}$ is the difference of the specific expenditures, dependent on operating expenditures, $\Delta \text{з}_{\text{т}}$ is the difference of the specific expenditures for fuel and energy for comparable variants, and Δy is the difference in the loss due to discharges.

The difference of specific fuel and energy expenditures characterizes the conservation of energy resources and can be determined as

$$\Delta з_{т} = з_{зт}\left(\frac{B_{зт}}{Q_{зт}} - \frac{B_{эс}}{Q_{эс}}\right), \tag{2}$$

and at $Q_{зт} = Q_{эс}$, which occurs upon compilation of alternative variants,

$$\Delta з_{т} = з_{зт}\left(\frac{1}{\eta_{зт}} - \frac{1}{\eta_{эс}}\right), \tag{3}$$

where $B_{зт}$ and $B_{эс}$ are fuel consumption for a traditional energy plant that utilizes a complete type of fuel and an energy-conserving plant (tons of conventional fuel), $Q_{зт}$ and $Q_{эс}$ are the useful energy consumption (tons of complete conventional fuel), $\eta_{зт}$ and $\eta_{эс}$ are the energy utilization factors ($\eta_{зт}$ is from 0.8 to 0.5 for traditional heat supply plants, while $\eta_{эс}$ = 1.0 to 2.0 or more for energy-conserving plants, for example, for TNU, due to the use of ambient thermal energy), and $z_{зт}$ are the specific expenditures for a complete type of fuel (rubles/ton of conventional fuel).

The difference in damage due to discharges Δy (upon observation of PDV and PDK) is dependent on the difference in the amount of burned fuel per unit of useful energy and of the specific damage due to discharges in the compared variants, i.e.,

$$\Delta y = \left(\frac{B_{зт}}{Q_{зт}} - \frac{B_{эс}}{Q_{эс}}\right) y_{B} = \left(\frac{1}{\eta_{зт}} - \frac{1}{\eta_{эс}}\right) y_{B}, \tag{4}$$

where Δy is the difference in damage due to discharges (rubles/t of complete conventional fuel) and y_B is the specific damage due to discharges per unit of burned complete type of fuel (rubles/t of conventional fuel).

When using different types of fuel to drive an energy-conserving plant and in a traditional plant, Δy is determined as

$$\Delta y = \frac{1}{\eta_{зт}} y_{B.зт} - \frac{1}{\eta_{эс}} y_{B.эс}, \tag{5}$$

where $y_{B.3T}$ and $y_{B.3C}$ are the specific damage due to discharges from combustion of complete type of fuel and of fuel utilized to generate energy to drive an energy-conserving plant (rubles/t of conventional fuel), respectively.

Selecting the type of complete fuel and energy to drive energy-conserving plants is related to optimization of the fuel-energy balance of the region, the structure of which can be changed significantly upon implementation of wide-scale measures on conservation of energy resources (gassification of a region). To determine the volume of conservation of energy resources and of the amount of complete type of fuel, one must also resort to using optimization models.

A method that determines the damage due to discharges Δy is rather complex and requires further studies. However, this is a separate direction of the studies, related to participation of scientists of different specialties on problems of ecology.

Taking into account the additional economic effect of energy-conserving measures in a region significantly affects both their ranking according to ecological impact, and the volume of feasible implementation of energy-conserving measures for the future.

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UDC 621.311.001.24

PROGRAM SYSTEM FOR DYNAMIC OPTIMIZATION OF ORS E TO STUDY DEVELOPMENT OF SYSTEMS-FORMING ELECTRIC NETWORKS OF ENERGY ASSOCIATIONS

917F0055B Riga IZVESTIYA LATVIYSKOY AKADEMII NAUK in Russian No 4, 1990 (manuscript received 26 Apr 90) pp 57-69

[Article by V. A. Dale, Z. P. Krishan, and L. V. Oleynikova, Physics and Energy Institute, Latvian Academy of Sciences]

[Text] General Characteristic

The program system (PK) is designed to study the main directions and principles of development of energy associations (EO). The most typical problems to be solved by using the ORS E program system are: 1) selecting the variants of development of systems-forming networks of energy associations at existing voltage by introducing new electric power transmission lines or by renovation of them; 2) substantiation of the introduction of electric power transmission at the highest voltage with regard to different times of implementation of the corresponding measures (for example, with regard to temporary operation of new electric power transmission at reduced voltage); 3) selection of the directions and voltage of new electric power transmission, designed to generate the power of new power plants; 4) refining the location of new power plants and substantiation of the plan of introduction of the generating capacities with regard to expenditures for development of the basic network of the electric power system; 5) substantiating the feasibility of introducing DC electric power transmission.

It was necessary to solve a number of methodical problems during development of the program system. They were related to the need to increase the number of variables and of the number of calculating modes, to optimization of the flow distribution in a complex network, which combines DC and AC electric transmission, with regard to limitations on capital investments. Using the ORS E program system, one can simulate the process of development of energy associations in different situations. Alternative measures on development of the network can be selected by using the program system, their efficiency for the entire range of anticipated future conditions can be determined with regard to space and time relationships, one can determine the factors that have a decisive influence on the optimal process of development, and one can

determine which of the alternative measures and when they should be implemented to guarantee an optimal value of the optimization criterion. Integral criteria for a sufficiently long calculating period are used when compiling the strategic variants of development. This is related to the fact that the relative effectiveness for the more promising strategies during the initial period is lower, compared to extensive variants of development. The number of compared versions of development is so great that substantiation of the solution is impossible without special program systems for dynamic optimization of the development of electric networks. Due to the uncertainty of information, substantiation and decision-making are carried out on a dynamic plan: as the initial information is refined, the solution is also refined.

The conditions of development includes information about the existing electric network, about the generating capacities and energy consumers, about future loads, about the calculating period, about alternative future measures, about restrictions, and about future technical and economic indicators.

The concept of development step is used to describe the calculating period in optimization problems. This is related to the fact that continuous progress of development of a system over time in practical dynamic calculation is always replaced by a discrete process. The time segment, during which the state of the system does not change, is considered a development step. The ORS E program system solves problems with number of steps up to 10.

The input information for the ORS E dynamic program system is information about the calculating plan of the network and the calculated operating conditions of the network during the calculating period, and also about the set of possible measures on development of the network, representing the area of optimization itself. The spatial relations and area of search for the optimal variant according to development steps are simulated on the basis of the calculating plan of the network object. The main concepts that characterize the calculating plan are as follows:

1) Notes. The combination of nodes of the network facility to be optimized is divided into groups (subsets), which are used to differentiate the technical and economic indicators. The nodes of this group are characterized by identical technical and economic indicators to compensate for the energy losses in the elements of energy associations. It is assumed in the ORS E when calculating the technical and economic indicators that energy losses in the elements of energy associations are covered in the outer nodes of these elements, i.e., in place.

2) Elements of network. Consideration of the following types of elements of the network is permissible: a) of an AC electric transmission line; b) of a DC electric transmission line; c) of a power plant (generators). The main notation of the element in the primary

calculating scheme are the numbers of its outer nodes. Transformers are not directly shown in the calculating scheme. Lines with different rates of voltages may arrive at one node. The main technical and economic characteristic of the element of an energy association is the number of the set of technical and economic data. Standardization of elements is introduced by using the indicated number. However, additional economic indicators (constant components of capital investments) can be used, by which individual features of separate elements are taken into account. These indicators are also used to take into account the economic indicators of transformer and converter substations.

3) Branches. The elements of the network are reflected in the calculating plan by branches. A branch is characterized by data of a specific element (AC or DC electric power transmission line, power plants) and by the number of parallel elements. Thus, a branch may also reflect several parallel LEP or generators with identical parameters. The primary scheme should contain both existing and future elements of the network. Thus, branches can be divided into existing and future branches.

The number of elements according to development steps t can be increased. Parallel branches that reflect the elements of the network with different characteristics are permitted in the scheme.

The connectedness of the calculating scheme is checked automatically by the programs of the system. The layout of the network is assumed connected if all its nodes, which can have a load, are connected to each other by existing or future branches. The characteristics which occur upon display of the electric network for dynamic optimization calculations include, for example, prohibition of elements with zero resistance (switches). One can require that one object be represented by several branches to display these measures. The calculating schemes of electric networks, compiled for dynamic optimization calculations, may have 100 nodes and 200 branches. Compilation of the calculating scheme for problems of optimizing the development of networks is a labor-intensive process and requires careful preparation of the input information even in the presence of check systems. But the labor expenditures to create the basic information about the calculating plan for optimization calculations of a given network are single- stage. This information is used repeatedly for a long period in studies of the development of EES. The calculating plan is only corrected during each study cycle.

Compilation of the task for optimization (determination of the area of search for the optimal solution) and display of it in the calculating plan of the network predetermine to a significant degree the process of optimization. The erudition of the investigator is of important significance for compilation of the optimization task. A set of alternative measures, which are described by means of variables, is determined in compilation of the optimization task. The problems to be

solved are those with discrete variables. Only two values are possible for each variable: 0--a measure corresponding to the variable is not implemented, and 1--the measure is implemented according to the variable. Each variable is characterized by an ordinal number and by a set of branches of the network, for which the number of elements of each branch per unit is increased on this and on subsequent steps of the optimization process after implementation of the variable at each step t.

When postulating the optimization problem, to be solved by using the ORS E, an alternative measure should be determined such that implementation of it would yield an energy effect (reduction of losses in the network, reduction of loads and so on).

The optimization program system for development of an ORS E uses variables of two types. Implementation of variables of the first type displays the measures on construction of electric power transmission lines over new routes, higher voltage lines and so on. No more than one new element appears in the corresponding future branches (with the number of elements in the primary scheme equal to zero). Implementation of variables of the second type shows the construction of new parallel LEP or installation of additional generators at electric power plants with the same parameters as existing plants, which is related to an increase of the number of elements both in existing and in future branches. When compiling the optimization task using the ORS E program system, one can impose restrictions on the possible period of implementation of variables, and the beginning and end of the period of implementation of alternative measures must be indicated.

It becomes necessary in optimization problems to take into account the dependence between implementation of measures. For example, to replace the wires on some electric power transmission line, the line must first be constructed. Logical restrictions must be established for Boolean variables in these cases. There are two main types of these restrictions:

1) Disjunction--states in which more than one measure (variable) from a given set is implemented are not permissible. Disjunction is used to simulate mutually exclusive measures on development of an electric network. This method of simulation can be used, for example, when selecting the optimal variant of the design version of an electric power transmission line (type of current, rated voltage, mark of wires).

2) Limitations on the sequence of implementing measures to develop the network. If j after i is given, implementation of the j-th variable is not permissible if the i-th variable has not been implemented. Limitations of type "j after i" are used to simulate measures which can be implemented only in a specific sequence. For example, if temporary use of an electric power transmission line at lower voltage with subsequent conversion of it to rated voltage is considered, this conversion can be implemented only after implementation of the first

measure--introduction of the electric power transmission line at the lower voltage compared to the rated voltage.

The use of logical restrictions reduces the dimensionality of the dynamic problems. Thus, for example, the presence of 10 logical restrictions with 20 variables causes a reduction of the number of possible states by approximately a factor of seven. Compilation of the optimization task is made difficult by the circumstance that the number of variables in dynamic optimization models is limited: the maximum permissible number is 64 variables. Accordingly, some aggregation (consolidation) of measures is possible.

Let us consider below the methods of simulation and optimization which are used in the ORS E program system.

Notations

q	--number of nodes in calculating plan;
n	--total number of branches in calculating plan;
$n_{ЛЭП}$	--total number of branches that show electric power transmission line (LEP);
$n_{ЭС}$	--total number of branches that show electric power plants (ES);
i	--ordinal number;
$c(i, t)$	--number of parallel elements of i-th branch on t-th development step, for LEP--number of parallel electric power transmission lines, for ES--number of units of same type;
$r(t)$	--number of calculated sets of loads, considered on t-th development step
$l(i)$	--length of electric power transmission line for i-th branch, km;
$P_L(i, t, j)$	--flow of active power in i-th branch on step t for i-th calculated load, MW;
$R(i)$	--coefficient proprotional to effective resistance, for determination of active power losses in one element of i-th branch, 1/MW;
$X(i)$	--coefficient proportional to reactance, for determination of reactive power losses, 1/MVA;
$Y_Э(i)$	--coefficient proportional to conductivity, for determination of flow of active power in one element of i-th branch (economical conductivity of branch 1), MW;
X_d	--longitudinal reactance of generator, percent;
$P_K(i)$	--specific active power losses to corona in i-th branch, kW/km;
$\cos \varphi$	--power coefficient of power flux, relative units;

$g_p(i)$ --specific susceptance of electric power transmission line, 10^{-6} cm/km;

$U_н(i)$ --rated voltage in i-th branch, kV;

$K_л(i)$ --capital investments in LEP, shown by i-th branch, dependent on its length, thousand rubles/km;

$K_{ка}(i)$ --capital investments in i-th branch, independent of its length (including those for substations), thousand rubles;

$K^{пост}_{эс}(i)$ --capital investments in i-th branch, shown by electric power plant, independent of number of units, thousand rubles;

$K_{бл}(i)$ --capital investments for installation of one unit in i-th branch, representing power plant, thousand rubles;

$P_{бл}$ --capacity of unit, MW;

$c_{топл}$ --specific fuel expenditures, kopecks/kW·hr;

$T_{макс}(i)$ --number of hours of utilization of installed power of i-th power plant;

$K_р$ --specific capital investments for installation of reactors, thousand rubles/MVA;

$K_с$ --specific capital investments in pressurizer on one electric power transmission line, thousand rubles/MVA;

$\gamma_р$ --degree of compensation of charging power of power transmission lines, relative units;

$\gamma_с$ --efficiency of capacitive power of electric transmission line, relative units;

$\alpha_{ка}$ --relative costs, dependent on capital investments $K_{ка}(i)$ for electric power transmission lines, relative units;

$\alpha_{эс}$ --relative costs, dependent on capital investments $K_{ка}(i)$ for power plant, relative units;

$\alpha_л$ --relative costs for depreciation and maintenance for electric power transmission lines, dependent on $K_л(i)$, relative units;

$\alpha_{пост}$ --relative costs, dependent on capital investments $K^{пост}_{эс}(i)$, relative units;

K_{peak} --coefficient for determination of expenditures for compensation of load reactive power losses, thousand rubles/year·MVA;

$З'_L(i, t)$ --relative expenditures for losses in i-th branch, dependent on loads, kopecks/kW·hr;

$З''_L(i, t)$ --relative expenditures for no-load losses in i-th branch, kopecks/kW·hr;

$T_r(j)$ --length of j-th mode, hr;

$З_Д$ --dynamic reduced expenditures;

$З_{Нб}$ --additional criterion for estimation of disruption of power balance conditions;

$З_П$ --additional criterion for estimation of violation of restrictions on power flows;

kk --number of parts of network unrelated to each other;

$P_Н(i, j)$ --power unbalance in j-th part of network for i-th set of calculated loads, MW;

R_f --hypothetical resistance;

L(j) --set of branches representing LEP for which restriction on power fluxes is disrupted, at j-th set of calculated loads;

$P_{доп}(i)$ --capacity per circuit, MW;

A and k --coefficients for calculation of additional criterion for estimation of violation of restriction on power fluxes are given in input information;

θ --number of years during which capital investments are made or annual costs vary;

$E_Н$ --normative factor of comparative effectiveness of capital investments;

$E_{НП}$ --normative factor of reduction of expenditures at different times;

$З_c(\vartheta)$ --reduced expenditures throughout system during year ϑ;

$З_c(\vartheta)$ --reduced expenditures throughout system at normal operating step;

$\vartheta_П$ --year of reduction of expenditures at different times (the first year of the calculating period is used as the year of reduction in the ORS E program system);

$\vartheta(t)$ --first year of t-th phase;

S(t) --coefficient of specific weight of expenditures $З_c(\vartheta(t))$ on t-th development step in specific function;

e(t) --state of network on step t (combination of implemented measures on development of electric power system during time up to t, inclusively);

f(t, e(t)) --minimum value of functional--specific function, corresponding to optimal process of development during t steps from initial state to some state e(t);

g(t, e(t)) --component of functional, dependent only on step t and state e(t), but independent of path of transition to given state e(t);

e(t, m) --states of development on step t with m implemented measures;

δ --constant, called critical gradient value;

grad*f(t, e(t, m))--relative maximum increase of functional for state e(t, m) according to comparison to functional for state e(t, m - 1) (relative gradient).

Indicators and Criteria of Variants

Active power losses ΔP(t, j) on step t with the j-th set of calculated loads are determined as the sum of load losses and no-load losses:

$$\Delta P(t,j) = \Delta P_{\text{н}}(t,j) + \Delta P_{\text{xx}}(t,j). \qquad (1)$$

The active power load losses in MW are :

$$\Delta P_{\text{н}}(t,j) = \sum_{i=1}^{n} \frac{P_L^2(i,t,j) R(i)}{c(i,t)}. \qquad (2)$$

The active no-load power losses in MW are:

$$\Delta P_{\text{xx}}(t,j) = \sum_{i=1}^{n_{\text{лэп}}} P_{\text{к}}(i) \cdot 10^{-3} \cdot c(i,t) \cdot l(i). \qquad (3)$$

The reactive power losses in the electric power transmission lines in MVA are :

$$\Delta Q(t,j) = \sum_{i=1}^{n_{\text{лэп}}} \left(\frac{P_L^2(i,t,j) X(i)}{\cos^2 \varphi \cdot c(i,t)} - g_{\text{p}}(i) \cdot U_{\text{н}}^2(i) \cdot 10^{-6} \cdot c(i,t) \cdot l(i) \right). \qquad (4)$$

The annual costs are determined as the sum of the costs for depreciation and maintenance, for energy losses and for compensation of the reactive power in thousand rubles/year:

$$И(t) = И_к(t) + И_п(t) + И_Q(t). \tag{5}$$

The annual costs for depreciation and maintenance in thousand rubles/year are:

$$И_к(t) = \sum_{i=1}^{n_{лэп}} И_{к,\,лэп}(i,t) + \sum_{i=1}^{n_{эс}} И_{к,\,эс}(i,t). \tag{6}$$

The annual costs for depreciation and maintenance for branch i, representing the LEP, in thousand rubles/year are:

$$\begin{aligned} И_{к,\,лэп}(i,t) = {} & K_{ка}(i)\,(c(i,t)-c(i,0))\,\alpha_{ка} + (K_л(i)\cdot\alpha_л + \\ & + g_р(i)\cdot U_н^2(i)\cdot 10^{-6}(K_р\cdot\gamma_р - K_с\gamma_с)\,\alpha_{ка})\,l(i)\,(c(i,t)-c(i,0)). \end{aligned} \tag{7}$$

The annual costs for depreciation and maintenance for branch i, representing the LEP, in thousand rubles/year, are:

$$\begin{aligned} И_{к,\,эс}(i,t) = {} & K_{бл}(i)\cdot(c(i,t)-c(i,0))\cdot\alpha_{бл} + \\ & + (K_{эс}^{пост}(i) + K_{ка}(i))\cdot\alpha_{пост}. \end{aligned} \tag{8}$$

The annual costs for losses in thousand rubles/year are:

$$\begin{aligned} И_п(t) = {} & \sum_{i=1}^{n_{лэп}} \sum_{j=1}^{\varphi(t)} \frac{P_L^2(i,t,j)\cdot R(i)}{c(i,t)} \cdot з'_L(i,t)\cdot T_r(j)\cdot 10^{-2} + \\ & + \sum_{i=1}^{n_{лэп}} P_k(i)\cdot з''_L(i,t)\cdot l(i)\cdot 8760\cdot 10^{-2}(c(i,t)-c(i,0)), \end{aligned} \tag{9}$$

The annual costs for compensation of reactive power in thousand rubles/year are:

$$И_Q(t) = \sum_{i=1}^{n_{лэп}} \frac{K_c\cdot\alpha_{ка}X(i)}{\cos^2\varphi c(i,t)} \cdot \max_{j=\overline{1,r}} P_L^2(i,t,j).$$

Capital investments are determined as the sum of capital investments in the electric power transmission line and the power plant:

$$K_{\Sigma}(t)=\sum_{i=1}^{n_{\text{лэп}}} K_{\text{лэп}}(i,t)+\sum_{i=1}^{n_{\text{эс}}} K_{\text{эс}}(i,t). \tag{10}$$

Capital investments for branch i, representing the LEP, in thousand rubles, are:

$$K_{\text{лэп}}(i,t)=\{K_{\text{ка}}(i)+(K_{\text{л}}(i)+g_{\text{р}}(i)\cdot U_{\text{н}}^{2}(i)\cdot 10^{-6}\times \times(K_{\text{р}}\gamma_{\text{р}}-K_{\text{с}}\gamma_{\text{с}}))\cdot l(i)\}\cdot(c(i,t)-c(i,0)). \tag{11}$$

Capital investments for branch i, representing the power plant, in thousand rubles, are:

$$K_{\text{эс}}(i,t)=K_{\text{эс}}^{\text{пост}}+K_{\text{бл}}(i)\cdot(c(i,t)-c(i,0)). \tag{12}$$

Dynamic expenditures are determined by the expression in thousand rubles/year:

$$З_{\text{д}}=\sum_{t=1}^{T}(E_{\text{н}}\cdot K_{\Sigma}(t)+И(t))\cdot S(t). \tag{13}$$

The dynamic reduced expenditures for the step process (the calculating period is divided into t normal operating steps, i.e., the loads for all calendar years of the step t are equal, while the scheme and parameters of the system do not vary during the step) are determined by the expression:

$$З_{\text{д}}=\sum_{t=1}^{T}З_{\text{с}}(\vartheta(t))S(t)+З_{\text{с}}(\theta+1)(1+E_{\text{нп}})^{\vartheta_{\text{п}}-\theta}, \tag{14}$$

where the coefficient of the specific weight of expenditures on the t-th development step is determined by the formula:

$$S(t)=(1+E_{\text{нп}})^{\vartheta_{\text{п}}-\vartheta(t)}-(1+E_{\text{нп}})^{\vartheta_{\text{п}}-\vartheta(t+1)}. \tag{15}$$

The ORS E program system permits the investigator to assign the value of coefficients S(t) for t = 1, 2, ..., T according to his discretion. If the values of S(t) are not assigned, they are determined by formula (15). An additional criterion of estimating violations of the condition of power balance on step t are determined by the expression in thousand rubles/year:

$$Z_{\text{нб}}(t) = \sum_{i=1}^{\varphi(t)} \sum_{j=1}^{kk} P_{\text{н}}^2(i,j) \cdot R_f \cdot A_{\text{св}} \cdot T_r(i). \tag{16}$$

The additional criterion of estimating violation of restrictions for power flows on step t is determined by the expression in thousand rubles/year:

$$Z_{\text{п}}(t) = \sum_{j=1}^{r(t)} \sum_{i=1}^{L(j)} (E_{\text{н}} \cdot K_{\text{лэп}}(i,t) + И_{\text{к. лэп}}(i,t)) \times \\ \times \frac{A}{r(t)} \left(\frac{abs P_L(i,t,j)}{c(i,t) \cdot P_{\text{доп}}(i)} - 1 \right)^k . \tag{17}$$

Model of Power Flows

The flow distribution of active power in the ORS E program system is determined by the minimum power losses in the network with regard to Kirchhoff's first law as supplementary conditions [1]. The expression for optimal power flows has the following form:

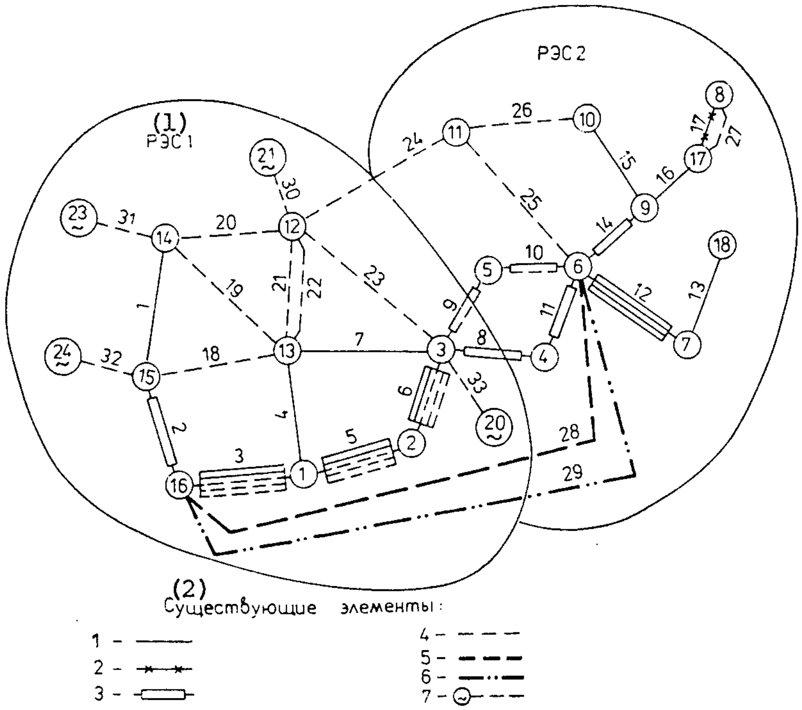
$$P_L(l) = Y_э(t)\,(\delta_э(i) - \delta_э(j)), \tag{18}$$

where $\delta_э(i)$ and $\delta_э(j)$ are the economic potentials for the initial and final node of branch l, respectively. The economic potentials are determined by a system of q equations:

$$\mathbf{Y}_э \cdot \mathbf{\Delta}_э = \mathbf{P}, \tag{19}$$

where $\mathbf{\Delta}_э$ is the vector column of the nodal economic potentials, **P** is the vector column of the loads of the nodes, and $\mathbf{Y}_э$ is the quadratic matrix of economic conductivity.

The active power losses in transformers in system-forming networks are relatively low compared to losses in electric power transmission lines. Therefore, the calculated layouts of the network do not contain transformer branches when determining the optimum flow distribution (see figure). Calculation of the optimal flow distribution permits convenient simulation of parallel operation of an AC network with DC elements [1].



Calculated Layout of Optimization of Development of Energy Association:
1--existing electric power transmission lines (LEP) of 500 kV; 2--existing LEP of 500 kV, temporarily using 220 kV; 3--existing branches with several elements; 4--future and alternative LEP of 500 kV; 5--future and alternative LEP of 1,150 kV; 6--future and alternative DC LEP of 1,600 kV; 7--future and alternative power plants

KEY:
1. Regional power plant
2. Existing elements

Target Function

The following target function is used when searching for the optimal variant of development:

$$F=З_{д}+Z_{нб}+Z_{п}. \tag{20}$$

The supplementary criterion of estimating the violations during the entire calculating period is determined by the expression:

$$Z=\sum_{t=1}^{T} z(t)S(t). \tag{21}$$

The ORS E program system takes into account restrictions on capital investments $K_{Д}(t)$ according to development steps t = 1, 2, ..., T. If the values of $K_{Д}(t)$ are not given, it is assumed that $K_{Д}(t) = 10^9$ rubles for t = 1, 2, ..., T.

Method of Optimization

All steps t = 1, 2, ..., T are considered sequentially during optimization. The optimal development during t steps to state e(t) is determined at each optimization step [2]. To do this, the following recursion relation is used:

$$f(t,e(t))=g(t,e(t))+\min_{\substack{e(t-1)\in e(t)\\ e(t-1)\in\{e(t-1)\}}} f(t-1,e(t-1)). \tag{22}$$

Only optimal initial states, which are local optimums according to the following condition, are sought during the next optimization step t

$$f(t,e(t))=\min_{e'(t)\in E} f(t,e'(t)). \tag{23}$$

The optimal initial states (OIS) and the corresponding values f(t, e(t)) are stored, which also permits one to determine the optimal development on step t + 1 during t + 1 steps to any state e(t + 1). The optimal initial states on the next step t is sought by sequential consideration of the subset of states {e(t, m)}, m = 1, 2, ..., where m is the number of implemented measures.

Because of the large dimensions of the problems of optimizing the ORS E program system, the approximate method of finding the optimal initial state is used.

In this case, the optimal initial states are selected by the feature

$$-\operatorname{grad}^* f(t, e(t, m)) \leqslant \delta. \tag{24}$$

The relative gradient is determined by the formula:

$$\operatorname{grad}^* f(t, e(t, m)) = \frac{f(t, e(t, m)) - \min\limits_{e(t, m-1) \in e(t, m)} f(t, e(t, m-1))}{f(t, e(t, m))} \cdot 100\%. \tag{25}$$

The search for the optimal initial states is stopped if no optimal initial states are found at given m. One could find all the local minimums of the target relation at $\delta = 0$ and upon retention of all optimal initial states at each optimization step and one could find the global optimum. However, this is unrealistic due to the large dimensions of the dynamic problems. The real dynamic optimization problems can be solved if the number of optimal initial states ($\delta > 0$) is retained at each development step by retaining only the optimal initial states with the best value of the functional for different competitive strategies. To reduce the set of optimal initial states in the program, one can also use the restriction form above FAA(t) for each step t = 1, 2, ..., T. Only those optimal initial states $e'(t)$ for which the following condition is fulfilled are retained during optimization

$$\frac{f(t, e'(t))}{\min\limits_{\{e(t)\}} f(t, e(t))} \leqslant FAA(t). \tag{26}$$

If FAA(t) is not given, it is assumed that FAA(t) = 1.4, since experimental and theoretical studies show that, if the values of the functional of some state differ from the minimum value more than 1.4, an optimal strategy may not pass through this state.

Pseudo-dynamic optimization is realized at FAA(t) = 1. Thus, the values of FAA(t) can be given in the range 1-1.4. The calculating time decreases as the value of FAA(t) decreases, but the probability of a loss of optimal strategy increases. The values of FAA(t) for subsequent optimization steps can be assigned less than for the initial values. The maximum possible number of retained optimal states is WM = 40. A decrease of WM reduces the time for optimization, but the probability of a loss of the optimal variant according to the integral target relation during the calculating period increases. Pseudo-dynamic optimization is realized at WM = 1. The procedure of optimization (22) for steps t = 1, 2, ..., T is performed repeatedly (by the iteration method) at $\delta > 0$.

Table 1. Optimized Measures (Variables)

i	(1) Наименование мероприятий	(2) Множество ветвей $\{L\}_i^1$	$\{L\}_i^2$	$\{LO\}_i$	(3) Ограничения $(t_н \div t_к)_i$	i_0
1	2	3*	4*	5*	6*	7*
1	Ввод электростанции в узле 14 (4)	31	—	—	2—2	—
2	Ввод электростанции в узле 15 (5)	32	—	—	2—2	—
3	Ввод электростанции в узле 3 (6)	33	—	—	2—2	—
4	Ввод ЛЭП кВ 12—14 (7)	20	—	—	1—3	—
5	Ввод ЛЭП 500 кВ 12—13 (8)	21	—	—	1—3	—
6	Ввод двухцепной ЛЭП 500 кВ 12—13 (9)	22	—	—	1—3	—
7	Ввод ЛЭП 500 кВ 3—12 (10)	23	—	—	1—3	—
8	Ввод ЛЭП 500 кВ 10—11—12 (11)	24, 26	—	—	1—3	—
9	Ввод ЛЭП 500 кВ 6—11—12 (12)	24, 25	—	—	1—3	—
10	Ввод ЛЭП 500 кВ 13—14 (13)	19	—	—	2—3	—
11	Ввод ЛЭП 500 кВ 13—15 (14)	18	—	—	2—3	—
12	Ввод 3-й параллельной ЛЭП 500 кВ 1—16 (15)	—	3	—	1—3	—
13	Ввод 4-й параллельной ЛЭП 500 кВ 1—16 (16)	—	3	—	1—3	12
14	Ввод 5-й параллельной ЛЭП 500 кВ 1—16 (17)	—	3	—	1—3	13
15	Ввод 3-й параллельной ЛЭП 500 кВ 1—2—3 (18)	—	5, 6	—	1—3	—
16	Ввод 4-й параллельной ЛЭП 500 кВ 1—2—3 (19)	—	5, 6	—	1—3	15
17	Ввод 5-й параллельной ЛЭП 500 кВ 1—2—3 (20)	—	5, 6	—	1—3	16
18	Ввод 2-й параллельной ЛЭП 500 кВ 3—5—6 (21)	—	9, 10	—	1—3	—
19	Ввод ЛЭП 1150 кВ 6—16 (22)	28	—	—	1—3	—
20	Ввод ЛЭП постоянного тока 6—16 (23)	29	—	—	1—3	—
21	Перевод ЛЭП с 220 на 500 кВ (24)	27	—	17	1—3	—

Notes: i--number of variable; $\{L\}_i^1$--set of future branches for which the number of elements assumes the value of 1 after implementation of the i-th measure; $\{L\}_i^2$--set of existing and future branches for which the number of elements increases by 1 after implementation of the i-th measures; $\{Lo\}_i$--set of branches for which conductivity is set equal to zero (the branch is disconnected) after implementation of the i-th measure; $(t_H-t_K)_i$--period of permissible implementation of i-th measure (t is the ordinal number of the optimization step); i_0--number of measure, after implementation of which implementation of measure i is permitted.

KEY:

1. Name of measures
2. Set of branches
3. Restrictions
4. Introduction of power plant in node 14
5. Introduction of power plant in node 15
6. Introduction of power plant in node 3

(Key continued on following page)

7. Introduction of LEP 12-14 of 500 kV
8. Introduction of LEP 12-13 of 500 kV
9. Introduction of two-circuit LEP of 12-13 of 500 kV
10. Introduction of LEP 3-12 of 500 kV
11. Introduction of LEP 10-11-12 of 500 kV
12. Introduction of LEP 6-11-12 of 500 kV
13. Introduction of LEP 13-14 of 500 kV
14. Introduction of LEP 13-15 of 500 kV
15. Introduction of third parallel LEP 1-16 of 500 kV
16. Introduction of fourth parallel LEP 1-16 of 500 kV
17. Introduction of fifth parallel LEP 1-16 of 500 kV
18. Introduction of third parallel LEP 1-2-3 of 500 kV
19. Introduction of fourth parallel LEP 1-2-3 of 500 kV
20. Introduction of fifth parallel LEP 1-2-3 of 500 kV
21. Introduction of second parallel LEP 3-5-6 of 500 kV
22. Introduction of LEP 6-16 of 1,150 kV
23. Introduction of DC LEP 6-16
24. Switch of LEP from 220 to 500 kV

The optimization is performed on the first iteration at some given value $\delta_{\text{нач}}$ and considers all variables. The value of δ decreases on subsequent iterations at given step $\Delta\delta$ ($\Delta\delta \leq \delta_{\text{нач}}$). Preoptimization of the optimal variant of development is performed. The ORS E program system presents the investigator the opportunity to perform preoptimization of some other variant as well if desired. In this case, the investigator should indicate the ordinal number of the preoptimized variant. If the ordinal number is not given, the optimal variant is preoptimized.

Thus, the optimization problem is solved with a reduced number of variables and with increased accuracy of finding optimal initial states. Optimization ends when the values of δ reach zero, i.e., when finding the exact values of the local minimums of the target relation, corresponding to the sought optimal initial states, it is guaranteed during searching for the optimal initial states.

Example

The calculating scheme for optimization of development of a system-forming network with refinement of the location of new power plants is presented in the figure. The considered energy association is separated into two regions--RES 1 and RES 2, having different cost of energy. The period to be studied is divided into three development steps with length of 5 years. A total of 10 calculated sets of loads is considered on each development step. Introduction of power plant 21 is provided during the first optimization step, and the problem of generation of power by this station must be solved. Another power plant must be introduced on the second step, and its location must be refined (node 14, 15 or 3). The main problem to be studied is that of selecting the variant of electric power transmission from node 6 to node 16. There

are three alternatives: 1) enlargement of the 500-kV network, 2) construction of a 1,150-kV LEP and 3) construction of a DC LEP. A special problem which is also studied in this problem is determination of the moment of transition of LEP 8-17, temporarily utilized on 220 and 500 kV (construction of a 500/220-kV substation at node 8).

Table 2. Logic Restrictions of Type "Or"

Number of restriction	Set of variables from which implementation of no more than one variable is permissible in one development variant
1	1, 2, 3
2	5, 6
3	19, 20

Table 3. Results of Optimization

(1) Номер переменной i	(2) Сроки реализации	
	t_i^1	t_i^2
1	2*	3*
1	1	1
2	—	—
3	2	2
4	1	1
5	1	1
6	—	—
7	—	—
8	1	1
9	1	—
10	—	—
11	—	—
12	—	3
13	—	—
14	—	—
15	—	—
16	—	—
17	—	—
18	2	2
19	3	3
20	—	—
21	1	1

*Notes: t_i^1--ordinal number of optimization step at which measure i was implemented in optimal variant of development; t_i^2--ordinal number of optimization step in variant for which the value of the functional is 1 percent higher than the minimum value.

KEY:

1. Number of variable i
2. Periods of implementation

A list of measures to be optimized according to development of the network is presented in Table 1. Variables 12-18 are those of the second type. They are described by a set of existing branches, for which the number of elements is increased by one by implementation of the measure. Variables 15-18 are described by two branches, while the remaining variables of second type are described by only one branch. The specific sequence of realizing them is observed when using variables of the second type and logic restrictions "after" are used (Table 1, column 7). Restrictions for the period of implementation of alternative measures (Table 1, column 6) and logic restrictions of the "or" type (Table 2) are also used in the considered example.

Introduction of these restrictions is determined by postulation of the optimization problem. For example, those layouts of the network are impossible in which branches 21 (variable 5) and 22 (variable 6) are present simultaneously, since these branches represent the same line in a one- or two-circuit version. Implementation of more than one measure from set 1, 2, 3 is also impossible, since only one new power plant is planned for construction during the second development step.

The results of optimization are presented in Table 3.

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